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A mobile phone-based sensor grid for distributed team operations

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THESIS

A MOBILE PHONE-BASED SENSOR GRID FOR DISTRIBUTED TEAM OPERATIONS

by

Peter J. Young

September 2010

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13. ABSTRACT (maximum 200 words)

In distributed warfare, warfighters operate in remote and austere environments with limited support from outside. In such situations, each team has to take care of its own safety and security. For operations that last over several days, even the most highly trained teams are vulnerable to fatigue, leading to a loss of focus during long periods of boring activities such as night watch. This can lead to mission failure and loss of life. We have developed a mobile-phone based system to help with the team's safety by providing real-time situational awareness to the team of its surroundings. We have built a sensor grid around the team by networking several mobile phones using Bluetooth and using their built-in components such as accelerometers to capture seismic signals and microphone to capture sound in the area. When the grid is breached by a human, animal or machine, the individual phones capture signals generated by the intruders' movements. These signals are then compiled and analyzed to calculate the position of the intruder and alert the team about its presence. In implementing this system, our goals were to minimize the additional weight to warfighter's gear, run the system on as low power as possible, and to make it easy to install and use the system.

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A MOBILE PHONE-BASED SENSOR GRID FOR DISTRIBUTED TEAM OPERATIONS

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

In distributed warfare, warfighters operate in remote and austere environments with limited support from outside. In such situations, each team has to take care of its own safety and security. For operations that last over several days, even the most highly trained teams are vulnerable to fatigue, leading to a loss of focus during long periods of boring activities such as night watch. This can lead to mission failure and loss of life. We have developed a mobile-phone based system to help with the team's safety by providing real-time situational awareness to the team of its surroundings. We have built a sensor grid around the team by networking several mobile phones using Bluetooth and using their built-in components such as accelerometers to capture seismic signals and microphone to capture sound in the area. When the grid is breached by a human, animal or machine, the individual phones capture signals generated by the intruders' movements. These signals are then compiled and analyzed to calculate the position of the intruder and alert the team about its presence. In implementing this system, our goals were to minimize the additional weight to warfighter's gear, run the system on as low power as possible, and to make it easy to install and use the system.

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I. INTRODUCTION

Small unit operations are often fast-paced and resource-constrained, and can often end up in situations where the safety of the unit as a whole rests on the shoulders of a watchful team member. For example, Army Special Forces, Navy Special Warfare, and Marine Corps Special Operations often deploy four-man teams deep in enemy territory for extended periods of time. Likewise, soldiers could be tasked to operate beyond the immediate protection of their unit, acting as an Observation or Listening Post where the team could be as small as two individuals. Fatigue may inevitably degrade the team's situational awareness. In such situations, the team risks ambush by the enemy, leading to loss of life or property. Such situations are also common in distributed warfighting where small units conduct operations in remote, austere environments where security is completely organic. The demand for technology-enhanced situational awareness is warranted for both the unconventional and conventional levels.

It would be helpful for the unit to be equipped with a lightweight, low-power surveillance capability that could raise an alert to the imminent danger in the vicinity. Such an alert could be raised as soon as a suspicious entity is detected within the range of the surveillance system. From a practical point of view, such a capability should be implemented without introducing significant additional

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Portions of this work have been previously submitted for publication in the SENSIAC and SPIE proceedings. See (Singh 2010, Young 2010).

weight, should use as little power as possible, and should be quick and easy to install and operate.

We have developed a system using current Smartphone technology to provide this lightweight and low-power sensor network. Modern Smartphone use a series of accelerometers to detect the movement and orientation of a phone. The most common uses of this information have been to flip screens from vertical to horizontal orientation and, in gaming applications, to simulate activities like driving a car or flying a plane. We have tested the sensitivity and accuracy of this accelerometer data. The accelerometer can be sampled over a hundred times a second; displaying micro changes in the gravitational pull on the device. These micro changes represent small vibrations in the phone. When affixed to the ground, the vibrations caused by footsteps and vehicles register as these micro changes in the accelerometer data. In addition, all phones are equipped with microphones for making phone calls. Smartphone can be programmed to interpret the sound received in decibels. Sound signals can also be sampled at over a hundred times a second. Sound can be another detection device for our sensor network. By combining the two, we increase the accuracy of intruder detection.

A. OBJECTIVES

Our primary objective in this research area is to determine the accuracy of Smartphone accelerometers and microphones and their abilities to detect the presence of movement. Our secondary objective is to determine if the Bluetooth networks are reliable enough to create an ad hoc network and transfer alerts to a human sentry. This work

will show the usefulness of this type of application. Our objective is not to endorse any particular type of Smartphone. It is to show that any Smartphone with good accelerometer and microphone installed has the capabilities to be a sensor, and an application could be added to it with little to no cost.

B. SMARTPHONE APPLICATIONS

The use of advanced Smartphone functionality requires the programming of applications to interface with operating system and hardware. Our applications focus mainly on the accelerometer and microphone. Using Objective-C and the IPhone SDK we have developed a sentry application and a base-station application to create alerts and transfer them to friendly lines.

1. The Sentry Application

The sentry application is loaded on the device that is placed forward of friendly lines. The application provides the following features.

a. Capture and analysis of the accelerometer and microphone data to make the determination as to whether there is movement in the vicinity. The device will have the option to give an alert siren or to create a silent alarm.

b. Ad hoc networking via Bluetooth. Currently Smartphone do not have the built-in ability to act as Wi-Fi hotspots. Therefore, Bluetooth is necessary for our networking. The system is designed to be used where there will be no other coverage. The sentry application will

communicate with the master device to transfer alarms silently from the sentry application to the main application.

Figure 1. Sentry Application

Figure 1 is a screenshot of the sentry application. It currently has the following functionality:

- Field to name the file where the data is stored
- Write button to execute write data to file
- Connect button to initiate the Bluetooth connection to the base station

- Text field where a simple Bluetooth chat function has been implemented.

2. Base Station Application

The base station application is kept inside friendly lines and communicates with the sentry devices and provides the user with the following features:

a. The user is able to choose the number of sentry devices to deploy. When the user chooses the number of sentries they want to deploy, an active sentry screen is displayed that reflects the deployment configuration. The display links graphics on the base station to the Bluetooth-connected devices, so when an alert is received the corresponding graphic lets the user know which device registered the alarm.

b. The base station acts as the server in the ad hoc Bluetooth network. This allows multiple devices to connect to the base station.

c. The user is able to choose how they wish to be alerted on an alarm. They are able to choose an alarm or just a visual alert. Different situations warrant a silent or auditory alarm, as discussed further in this paper.

Figure 2 is a screenshot of the current base station application. It currently has the following functionality:

- Buttons to choose up to four nodes to connect to
- Connect button to initiate the Bluetooth connection to the sentry station
- Text field where a simple Bluetooth chat function has been implemented.

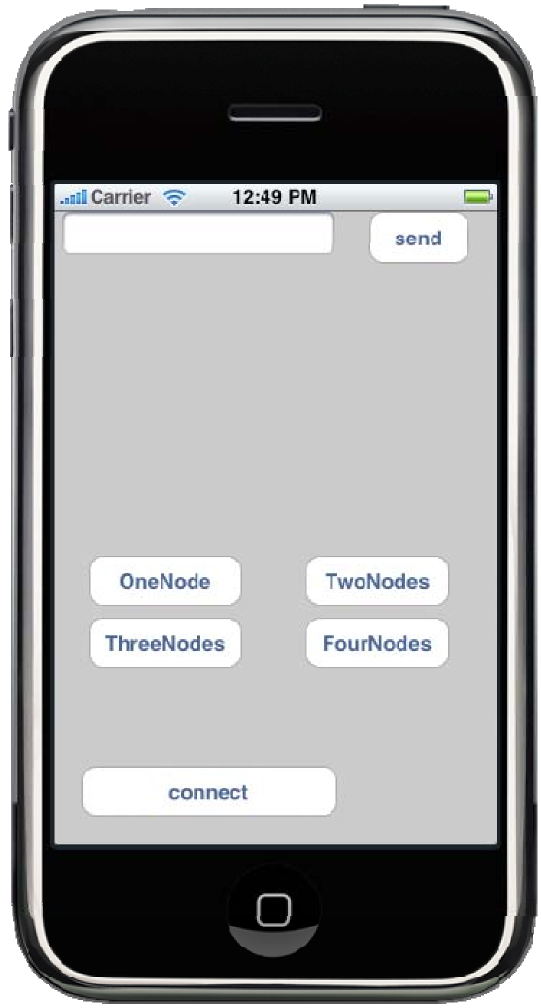

Figure 2. Base Station

C. SMARTPHONE REQUIRED CAPABILITIES

For the Smartphone to be able to act as a sensor in the manner we propose, it must provide the following capabilities for data collection:

Three accelerometer values:	X, Y, and Z-axis
Sampling:	100 samples per second
Alert:	Playback auditory alarm
Data Transfer:	Bluetooth capability to connect to server device
Sound Recording:	microphone that can convert signal to Db

D. CHAPTER OUTLINE DESCRIPTION

Chapter I gave a brief introduction to the motivations and usefulness of Smartphone sensors. Smartphone type devices are already being deployed, and we believe their capabilities are being underutilized. This chapter also discussed the primary objective of this work, a description of the applications and the system requirements of devices. Our approach is to use a minimal amount of gear, providing the users with added functionality, without added weight to carry.

Chapter II provides a description of the IPhone, which we used in this project, and how we accessed and filtered the accelerometer data. The processed accelerometer data was used to detect footsteps.

Chapter III describes how we accessed the microphone on the IPhone and stored the data. It shows how the raw data, when graphed, shows audio events as definite spikes in the

decibel level. The chapter also describes how footfalls and digging event appear at regular and predictable intervals.

Chapter IV gives a description of the experiments that were performed. The methodology is described and the results are shown in graph form. The experiments performed ranged from simple tabletop taps to digging holes at varying distances. The chapter continues on to describe some of the future tests that need to be carried out as this project moves forward. It concludes with the authors' conclusions on the validity and results of the experiments.

Chapter V is our vision of the employment of the sensor. The Marine Corps standard operating procedure is used in conjunction with the abilities of the sensor to provide some ideas of where and in what situations the phones should be employed. This ranges from offensive ambushes to a defensive warning grid.

Chapter VI is a summary of the thesis with my conclusions about the project. It also provides guidelines for the future of this project. It describes this author's ideas for what needs to be completed before this project can be presented real world applications.

II. ACCELEROMETER AND FILTERING

This chapter is an overview of the Apple IPhone 3GS's accelerometer. We discuss the specifications of the device so as to give a frame of reference for other smartphones that have similar or better accelerometers. We also discuss the coding involved with reading and interpreting the data from the accelerometer. The chapter also shows a sample graph of the data collected and finishes with an explanation of how signals are interpreted as human footsteps vice random seismic events.

In order to use the Apple IPhone 3GS in our research, we used unlocked versions of the phone to facilitate data transfer during the testing phases. The IPhone uses the LIS302DL accelerometer, which has dynamically selectable full scales of ± 2g/± 8g, and is capable of measuring accelerations with an output data rate of 100 Hz or 400 Hz. In testing it, we noted that at 100 HZ we were getting, on average, 98 readings per second. Sampling at higher rates than 100 Hz may be capable with the LIS302DL but the ability to track, process, and write the received data will cause the IPhone to drop readings. The ability to detect footsteps does not require more than 100 Hz.

Our current implementation has not fully put all data processing on the device. We have found it necessary to store the data and move it off the device for processing. Currently, 100 values per second are written to a text file and this text file is transferred off the device to allow us to levy the power of programs like Matlab and Octave to

process the data. We are currently using a combination of a low pass filter on the phone and a 4^{th} order Butterworth filter off the device, which has been giving us some distinct events that can be used to raise an alert. Filtering techniques can continue to be improved in order to make the device more and more sensitive. This filtering will then be written on the phone so the phone can filter the data as it comes in and make instantaneous decisions on alerts.

A. IPHONE ACCELEROMETER ACCESS

To understand the capabilities of the IPhone, it is necessary to review how the IPhone uses Objective C and COCOA to access the phones hardware. Objective C imports frameworks in similar fashion to Java and other object-oriented languages. Where Java has Application Programming Interfaces (API) to interface with different hardware devices, Objective C has "delegates". In IPhone, the delegate we are interested in is the UIAccelerometerDelegate. It defines a single method, didAccelerate, that allows us to receive acceleration-related data from the system (Apple Inc, 2008). This functionality first became available in IPhone OS 2.0.

The UIAccelerometerDelegate starts a secondary thread that fires the didAccelerate method at a rate that is set by the user. For our purposes, we fired the method 100 times per second. While in the didAccelerate method, it is possible to receive a float value that gives the number of Gs (multiples of gravity) that the accelerometer is experiencing on each of the three axes. Below is an example

of a didAccelerate method that demonstrates how one would read accelerometer values and output them to a predefined set of labels.

```
-(void)accelerometer:(UIAccelerometer*)accelerometer
          didAccelerate:(UIAcceleration *)acceleration
{
      labelX.text = [NSString stringWithFormat:@"%@%f",
                    @"X: ", acceleration.x];
      labelY.text = [NSString stringWithFormat:@"%@%f",
                    @"Y: ", acceleration.y];
      labelZ.text = [NSString stringWithFormat:@"%@%f",
                    @"Z: ", acceleration.z];}
```

B. ACCELEROMETER FILTERING

The accelerometer in the IPhone produces much seismic noise. This is the biggest problem that we have been faced with in our research. Even when sitting on a perfectly still surface, there is a baseline of noise received by the phone, which has a tendency to mask usable data. We have implemented different types of filters with varying success. Figure 3 shows a plotting of activity during a static period. There was no movement of any kind during this 25-second period. It is clear that there is some activity occurring to give the accelerometer these constantly changing values.

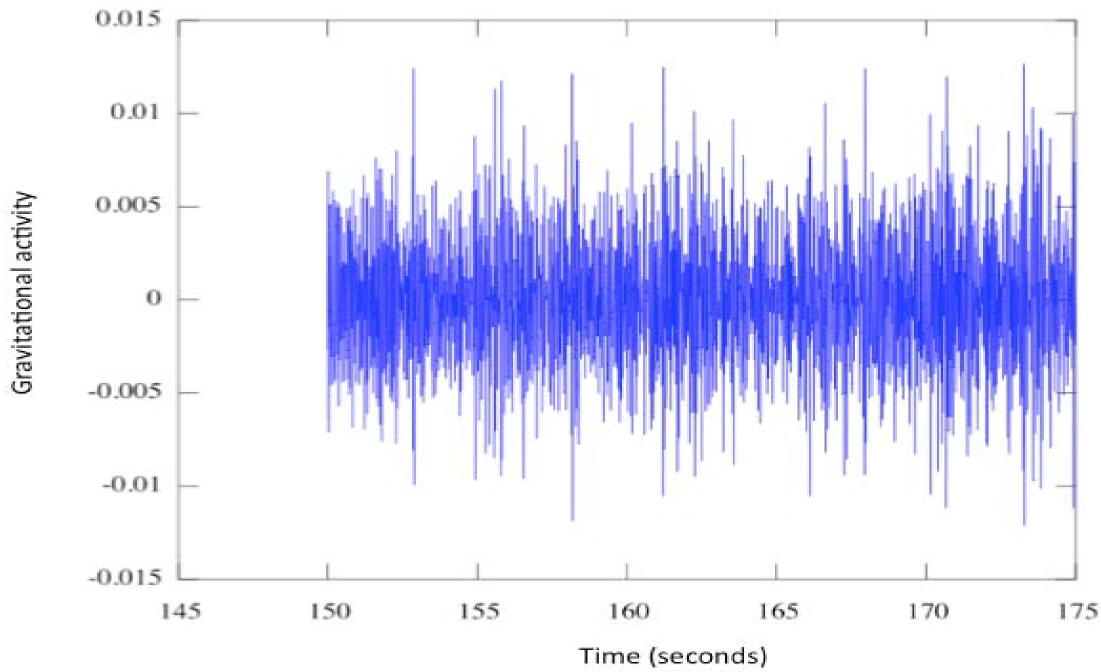

Figure 3. Noise Example

By using a combination of low-pass 4th order Butterworth filters and integrating audio detection, we have seen clear footstep signals rise above the noise, which we can use to generate an alert signal. Further filtering will cause too many false negatives for the alarm to be useful at any distance of more than a few feet.

1. Onboard Filtering

The current smoothing technique used in the didAccelerate method is a standard low-pass filter, taken from the IPhone Developers site. It removes the baseline gravity and only measures the instantaneous changes in acceleration. This takes all three values and sets their baseline to 0.

```
#define kFilteringFactor 0.1
accelX = acceleration.x - ( (acceleration.x *
      kFilteringFactor)+(accelX*(1.0-kFilteringFactor)) );
```

This filtering allows us to combine the three values making vibrations felt on two different axes to compound their effect. The values are combined by taking the square root of the sum of the squares of the three axes. When the three axes are combined this way, any motion registered on any of the three axes will affect the result.

2. Off Device Filtering

The data that has been transferred off the device for use in more powerful analytical languages is stored in the form of a text file and contains a timestamp, accelerations in x, y, and z, and the sound decibel value. We have used Octave and Matlab to perform analysis on the data. Below is a sampling of how the data was stored on the text file. The time stamp shows the date and time down to the millisecond.

06/04/2010 10:30:50:26AM x:, 0.036224 ,y:, -0.996170 ,z:, -0.108673 ,comb:, 0.812215 ,sound:, -53.422604

06/04/2010 10:30:50:29AM x:, 0.018112 ,y:, -0.996170 ,z:, -0.108673 ,comb:, 0.730586 ,sound:, -54.087948

06/04/2010 10:30:50:30AM x:, 0.018112 ,y:, -0.996170 ,z:, -0.108673 ,comb:, 0.657528 ,sound:, -54.087948

Once we have the data transferred off the device, we process it using Octave. The data is read into a matrix and run through a 4th order Butterworth Filter with user-defined cutoff frequencies. The data is then plotted against time

and observed visually. Figure 4 shows the results of filtered data of a series of taps while the phone rested on a tabletop.

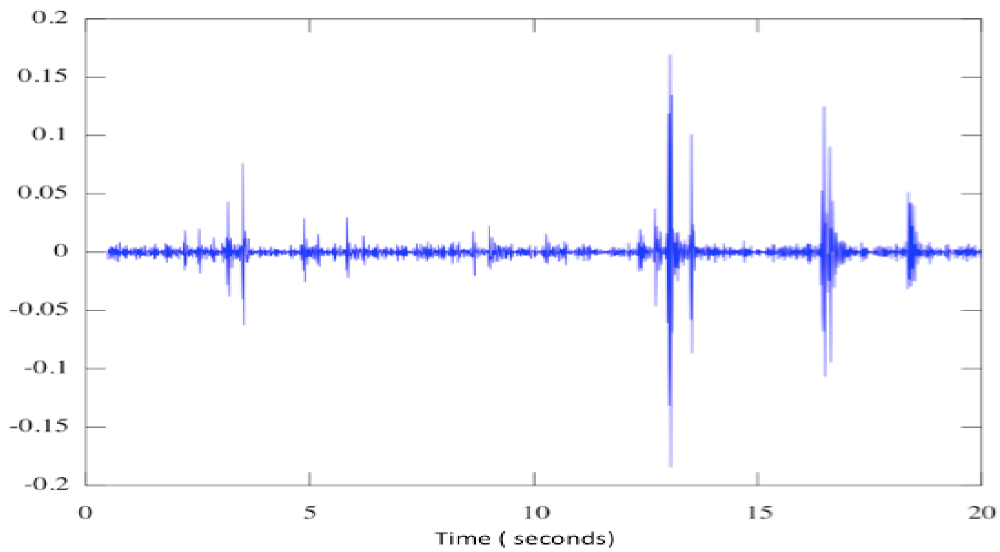

Figure 4. Example Seismic Plot

a. ***Kurtosis***

Kurtosis is the statistical measure of the peakedness of the signature (Succi, Clapp, Gampert, & Prado, 2001). The formula below is how these values are calculated. A group of samples is taken spanning a period of time.

$$Kur = \frac{\dfrac{\sum_i (x_i - \mu)^4}{N-1}}{\left(\dfrac{\sum_i (x_i - \mu)^2}{N-1}\right)^2}$$

Where x_i is the current sample and μ is the computed mean over N samples;

It is determined from the 4^{th} and 2^{nd} moments of the signal peak. Kurtosis can be described as how spiky the amplitudes are in the data; it is taken of a sample of time and compared to a baseline.

If the kurtosis is significantly higher, then an alert can be raised. Instead of doing extensive baseline experiments and storing baseline information we propose to compare the kurtosis of the current period with a period 5 to 10 seconds prior. This allows us to have a running average kurtosis, and if it spikes, we know to raise an alarm. In Figure 5, a simple visual analysis of the data shows that in sample 1 the kurtosis is clearly lower than in sample 2. This would demonstrate alert conditions on the sensor.

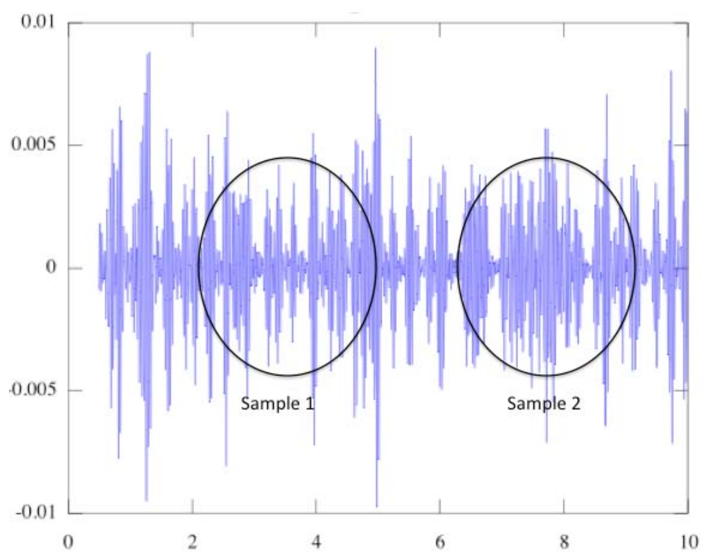

Figure 5. Kurtosis Example

C. SUMMARY

This chapter has discussed the hardware and software that the IPhone 3GS uses to recognize movements in the

phone. The accelerometer measures the values on three axis and we are able to detect very fine vibrations in these readings. We also showed what the acceleration values look like when graphed against time. The chapter finished by discussing how spikes in the acceleration data can be interpreted as a human presence.

The next chapter discusses how we used the microphone equipped for voice calls to detect human presences from the noise made by their footsteps.

III. AUDIO PROCESSING

A. BACKGROUND

Analysis of vibration data can be enhanced by adding the analysis of sound passing through the air and recorded by traditional microphones. Microphones pick up less of the natural frequencies of the ground than vibration sensors, and generally record clear impulses for footsteps and other percussive sounds of interest. Most of these signals show a broad band of frequencies so frequency analysis is not especially valuable. Time-domain analysis of the vibration signal can be used to find audio peaks. Microphones do pick up more spurious signals than vibration sensors due to many common forms of background noise such as motors. However, a vibration peak that coincides with an audio peak tends to be more likely to be meaningful than one that does not, and thus audio provides confirmatory data for vibration analysis.

Sound processing operates on a similar fashion as the accelerometer data. The IPhone microphone has a frequency response from 20Hz to 20,000Hz. It supports a wide variety of audio formats. Our tests stored the data in a .wav format. We are currently testing the benefit of using different audio formats. The data is plotted in a similar way as the seismic data. The data is the strength of the signal plotted against time in milliseconds. The signal strength in decibels operates in a range from -60 (quiet) to 0 (loud). Below is a sample graph of an audio signal.

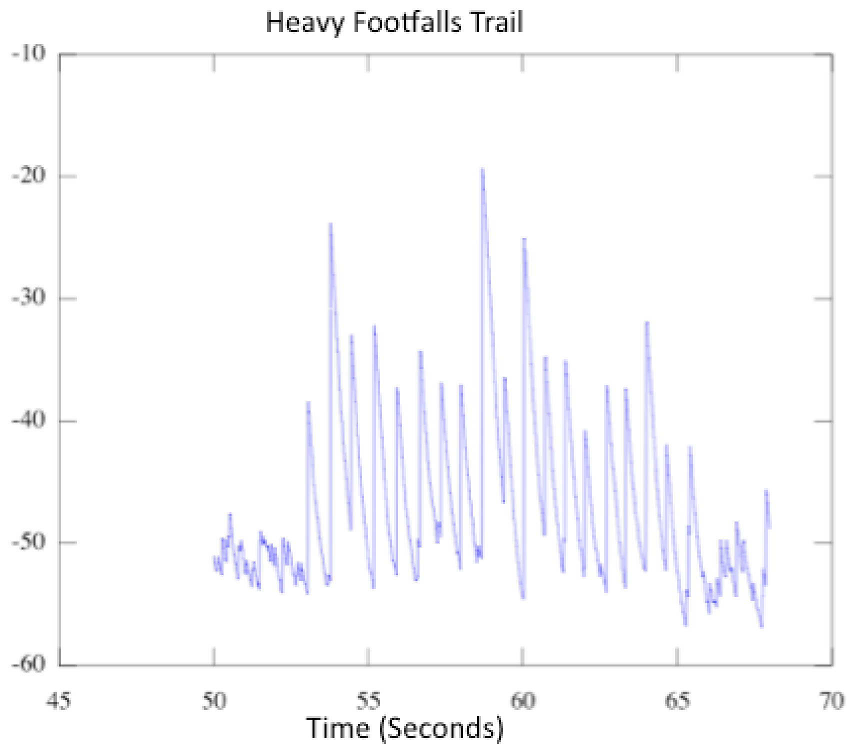

Figure 6. Example Audio Plot

B. IPHONE AUDIO RECORDING

Our Objective C project implemented the AVAudioRecorderDelegate to access the microphone (Apple Inc., 2009). The AVAudioRecorderDelegate implements methods to handle the recording such as the recording process and handling errors. When our program is run, the IPhone starts a recording method where several settings are initalized such as the sample rate and location of the stored recording. To process audio data, we must save the sound recording. We need to further test recording lengths to determe the maximum amount of time we can record before running into memory and hardware errors. We used a standard

timer thread that fired a function 100 times per second. It was in this method that we wrote the sound values to the same text file that the accelerometer data is stored. The result is a single text file that includes the three accelerometer values and the sound in decibels. We can take this file off the IPhone for data processing using stronger programs such as Matlab and Octave. When the suitable algorithms are found, the sound processing will have to be done onboard the IPhone to provide real-time alerts.

C. AUDIO PROCESSING

Positive peaks of the energy detected by an audio sensor generally signal interesting phenomena. To find them, we adapted techniques from our research on audio tracking (Rowe, Reed, & Flores, 2010). We first subtract the signal from its mean value over the entire recording interval to eliminate low-frequency components. We then set to zero all portions below a threshold set as a multiple of the standard deviation of the signal; 1.5 times the standard deviation worked well in our experiments. The reason for ignoring negative portions of the signal is that footsteps and other percussive sounds generally create a momentary increase of sound pressure stronger than the subsequent negative peak, and thus is easier to detect.

We then look for peaks in the remaining signal. At a sampling rate of 100 hertz, typical footstep peaks will cover 3-20 samples and we did not find a need for further smoothing. We currently search for values that are the maximum in a centered window of seven samples, and found this to be adequate coverage. The time and height of each peak found are calculated and stored, as well as peak

narrowness (ratio of average height before and after 0.045 seconds to the peak height), and asymmetry (ratio of the difference of the heights 0.045 seconds before and after to the peak height).

For footsteps, we exploit the observation in (Sabatier & Ekimov, 2008) that normal footsteps of the same walker are not less than 0.48 seconds apart and no more than 0.80 seconds apart. We search for sequences of peaks that obey this constraint. We explored using the narrowness and asymmetry to help with matching, but found they did not help much because footsteps from the same pedestrian can vary significantly in shape.

The best clue to distinguishing footsteps from background noise is in their periodicity. Thus, we search for groups of two, three, and then four footsteps in sequence. Since nearly all clear footsteps will occur at least in groups of four, sounds that do not belong to such a sequence are unlikely to be footsteps. We rate members of sequences by the evenness in time of the peaks in the sequence. Sequences of footsteps at a good distance from the microphone should also show only a single local maximum of the peak heights at the time of closest approach. However, nearby footsteps may show two maxima with typical sound-recording microphones with a narrow angle of sensitivity (directionality), one for the closest approach and one for the angle most along the axis of the microphone. The IPhone audio microphone is directional, but the vibration sensors are not.

For excavation behavior, we will also see periodic peaks of 1 to 10 seconds, but they will be less regular.

Peaks should be roughly the same width, so this gives us an additional clue. We are also starting to search for the human voice as it indicates conversations and is usually a negative clue (a clue arguing against concealment and suspicious behavior).

D. SUMMARY

In this chapter, we have discussed the hardware that is used in the IPhone 3GS as it relates to audio reception. We explained the packages imported that gave us the ability to process audio and showed a graph of the sound values when compared to time. The chapter finishes with an explanation of how the audio signals can be interpreted to make a determination of footsteps versus other auditory events.

The next chapter brings us to the experimentation phase. There is an overview of the systems design, and we discuss some of the experiments conducted, as well as the validity and meaning of their results.

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IV. SYSTEM ARCHITECTURE AND EXPERIMENTS

A. BACKGROUND

The tests described in this section were all used a proof of concept to determine whether the accelerometer and equipment is sensitive enough to detect the vibrations produced by the footsteps of a bypassing human. In the diagram below, we can trace the workings of the client application from the data received by the phone to the off device data processing. The current testing did not use the server application.

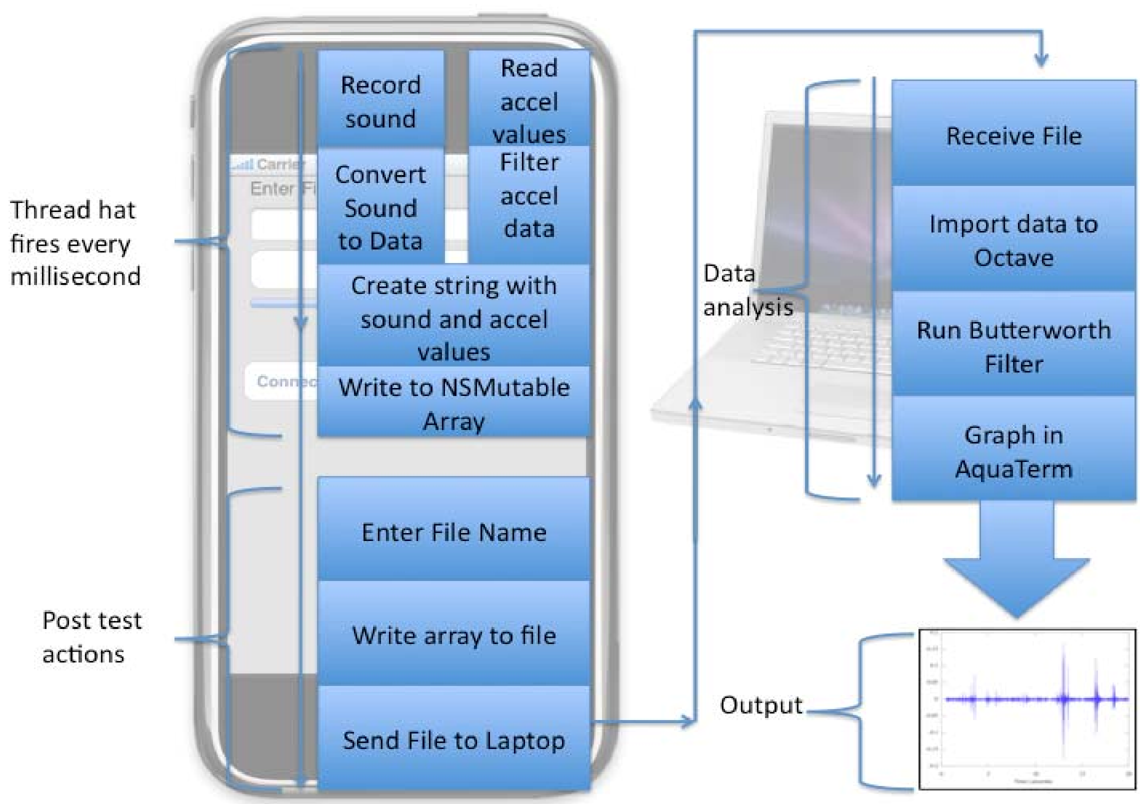

Figure 7. Flow of Control

Original experiments were conducted indoors at the Naval Postgraduate School Computer Science Lab. The device performed well on tabletops and floors. With these promising results, the tests were taken outdoors. Our testing to date has been on hard packed dirt surfaces; these will give us the best seismic wave transfer in an attempt to prove the abilities of the phone. We took the testing to the back roads of the former Fort Ord. This made sure we were a great distance from any possible contamination. The stand that was used was constructed from parts bought from the local hardware store for less than four dollars. (Figure 8)

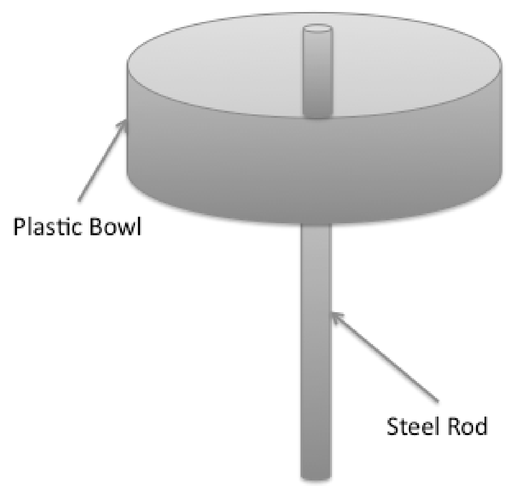

Figure 8. Stand Example

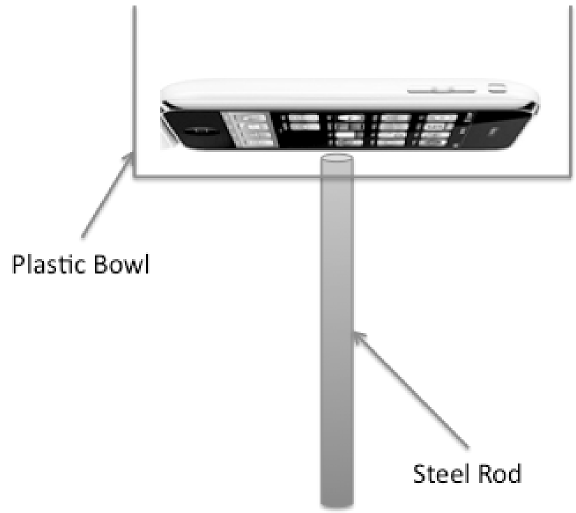

Figure 9. IPhone Placement

B. PROCESS

The Phone was secured to the steel rod inside the plastic bowl. The idea is that the seismic vibrations, that travel in the top 6”-8” of the soil, will transfer to vibrations in the steel rod. The rod will then vibrate the phone. The plastic bowl operates in the similar fashion as a phonograph horn amplifying the vibrations. We experimented with several different orientations of the phone. Our best results came when we laid the phone face down and balanced on the rod, as seen in Figure 9. We used the following procedure.

1. Dig small hole to get the phone as close to ground level as possible, about two to four inches deep. Geophones and devices like ours become more effective the closer the device is to surface level.

2. Place phone in stand and start the application. Beginning the application, in our program, begins the process of recording seismic and audio values at a rate of 100 times per second. While the program is running, these values are stored in an NSMutableArray.

3. Begin filming. All experiments were filmed with video to have a visual record of the subject's relation to the phone at any given time. This can then be translated into actions that are correlated with events in the data.

4. Tap phone 5 times to create a reference point in data to begin test. A large audio and seismic event can be linked to an action in the video to create an accurate events timeline.

5. Run test with periods of walking and periods of no movement. The periods of no movement were just as important as the periods of activity. We used these periods to form the baseline of events that we attempted to filter out.

6. Transfer data to a computer for filtering and analysis. We are currently doing this manually using the Jailbroken IPhone application called NetATalk.

We also found it useful to run two sensors in close proximity to each other. This allowed us to vary the two sensors and look for more results. For example, we found that a phone in a horizontal orientation gave better results than a phone with a vertical orientation. We were also able to use a comparison of two signals to cancel out ground noise. If the same spike is noticed at two different sensors, it is unlikely that it is a human causing the

alert. It is also our goal to eventually use the strength of signal from two different sensors to give a more accurate location of the event. In Figure 10, we would expect to see a stronger event signal on Sensor 1 than Sensor 2. By comparing the two signals, we would be able to determine that the subject is passing between the two sensors but is closer to Sensor 1. We could accurately track their direction based on this data.

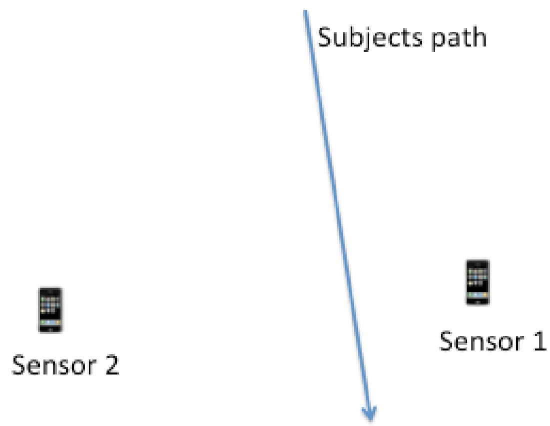

Figure 10. Dual Sensor Example

C. RESULTS

In this section, we discuss some tests we conducted and show the seismic activity received by each test. Each graph will represent the norm of the acceleration (combined X, Y, Z accelerometer values) plotted on the Y axis of the graph with time in seconds plotted on the X axis. We are looking for spikes in the data that show a strong vibration or a wider period of a weaker vibration that show other activities.

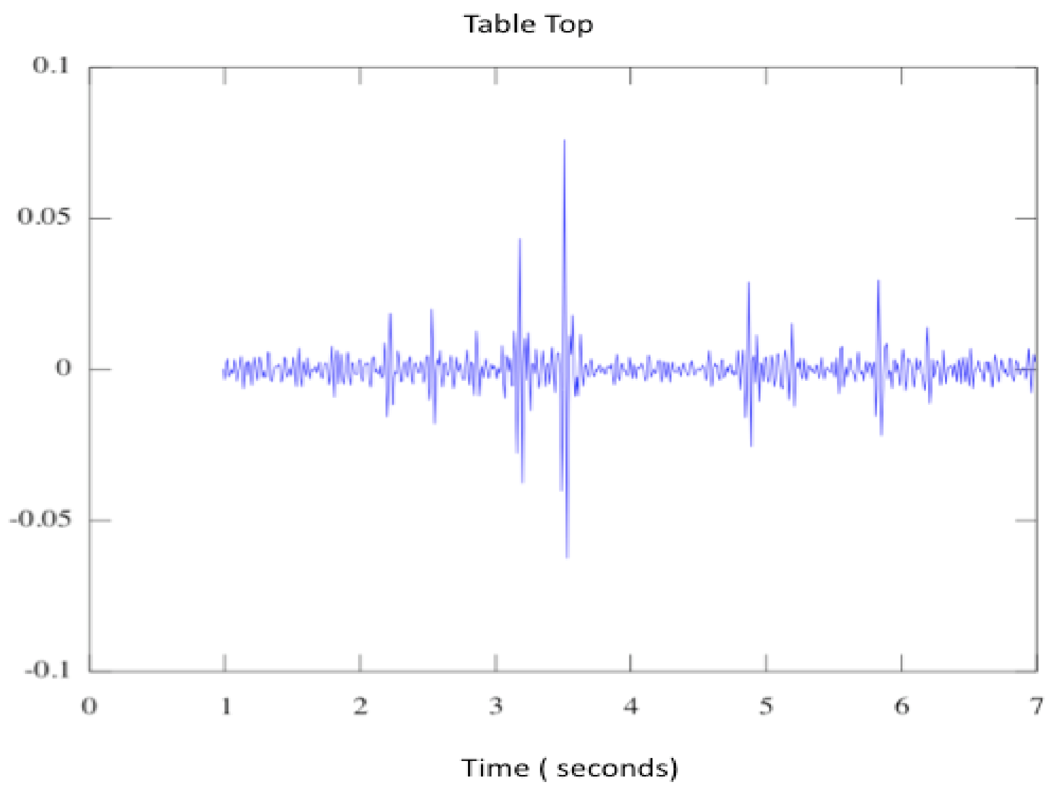

Figure 11. Table Top Results

Figure 11 depicts one of our first tests. The phone was laid flat on a table and the table was tapped at a distance of 5 feet from the phone. The two sets of five taps are clearly visible from second 2 through 3.5 and 4.5 through 6.

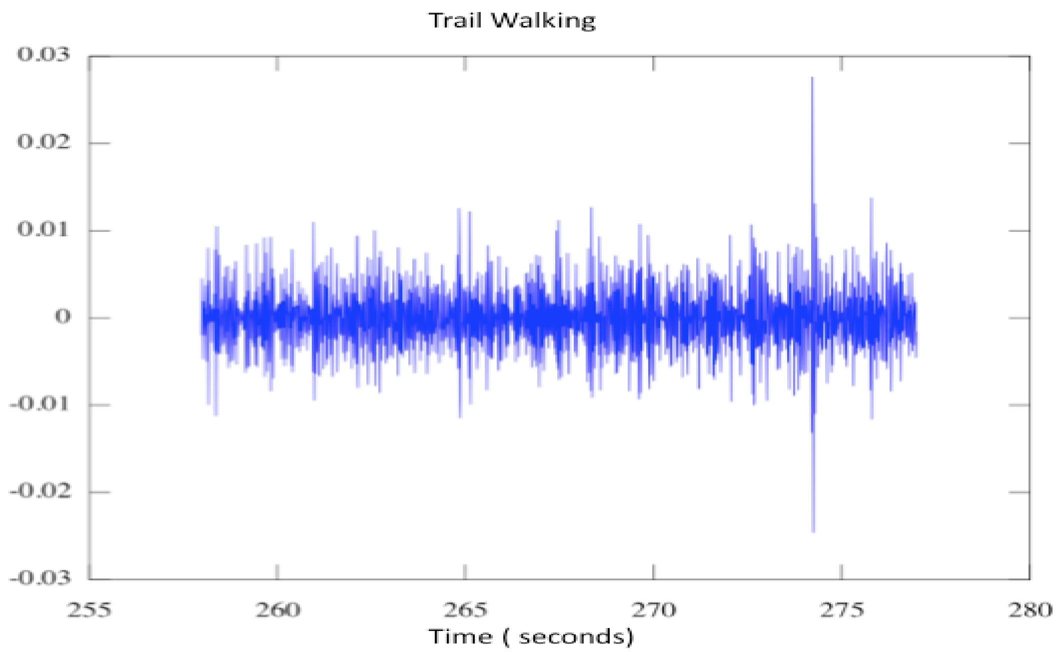

Figure 12. Trail Example (Seismic)

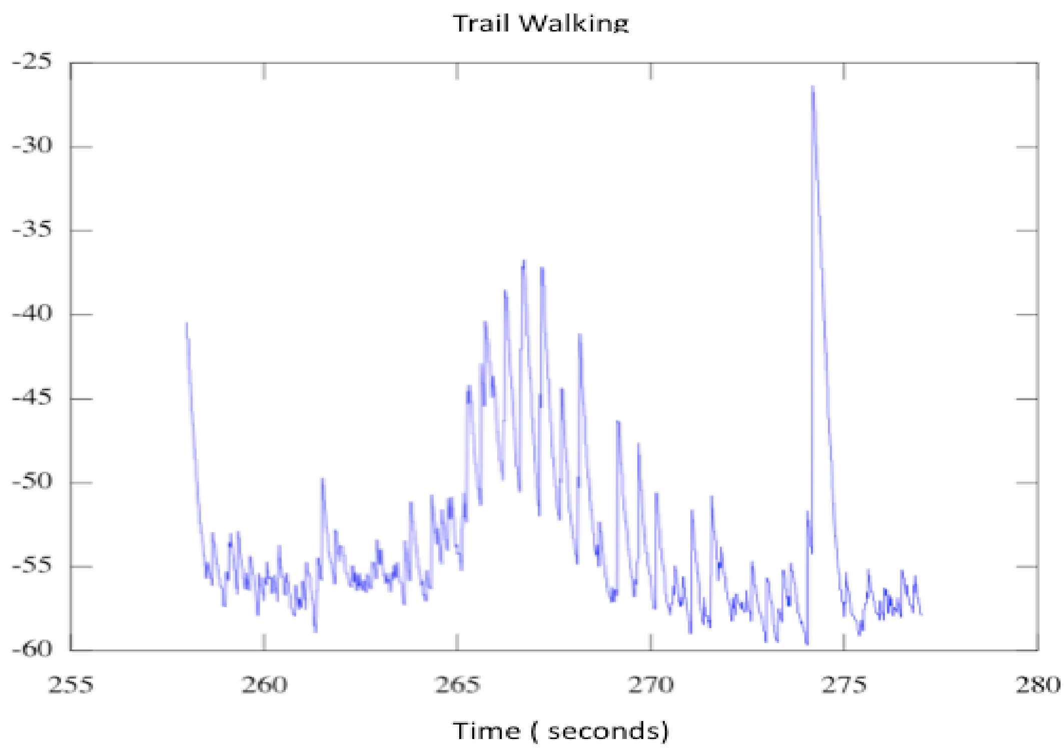

Figure 13. Trail Results (Audio)

Figure 12 represents a test that occurred on a hard packed trail. The sensor was set up to the side of the trail and the subject was a 200-pound man wearing boots. He walked down the trail passing directly by the sensor around second 267. There are several peaks in the middle of the time frame showing the approach of the subject. The peak at 274 was a hammer strike near the sensor to mark the data.

Figure 13 shows the processed audio of the same test. The footsteps are clearly visible. The sound values are stored as a running average of the surround second, this is why there is a hump in the middle, and it shows the approach and retreat of the test subject.

We also conducted some experiments of our ability to detect digging. This would be useful to determine if an enemy is attempting to dig under a fence or place an Improved Explosive Device (IED). Digging produces a much higher seismic signal than simple walking, and a phone should detect this action at a further distance. We were able to see some activity when digging occurred within a few meters of the phone but will test larger distances.

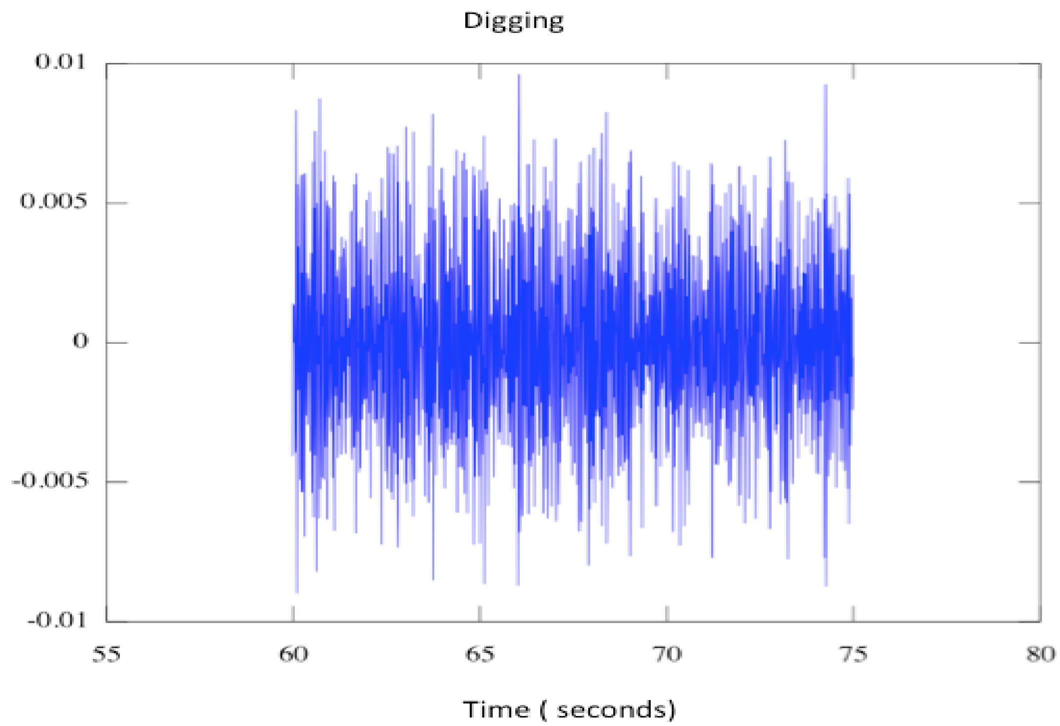

Figure 14. Digging Results

Figure 14 is of a seismic test where we performed digging with a full-size shovel at a distance of 10 feet. The figure shows a 15-second interval where there were shovel strikes at 65 and 73 seconds. The graph and data did not reveal activity above the noise to the level that we could provide an alert.

A second test was performed, this time we used two phones. We placed one phone five feet from the digging site and the other ten feet from the dig site. When this data was analyzed, I used a much stricter high cut and low cuts on the Butterworth filter. I used a value of 45 for the low cut and 50 for the high cut. This effectively grouped the data a little more and made some peaks much more visible.

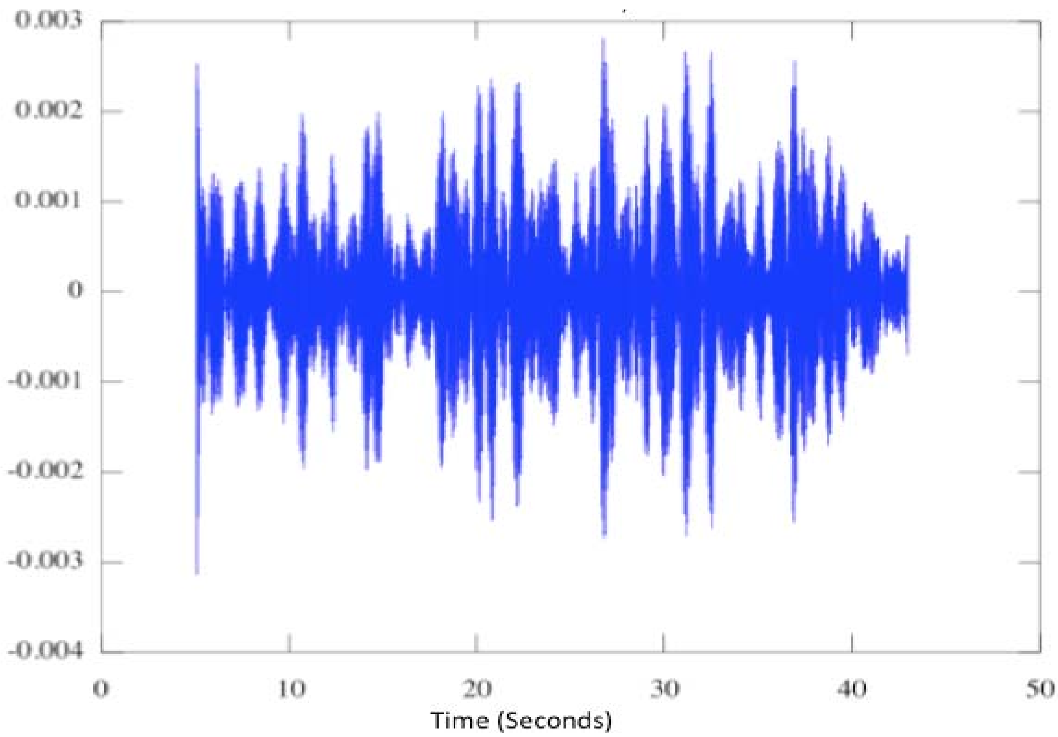

Figure 15. Second Digging Results (5 Feet)

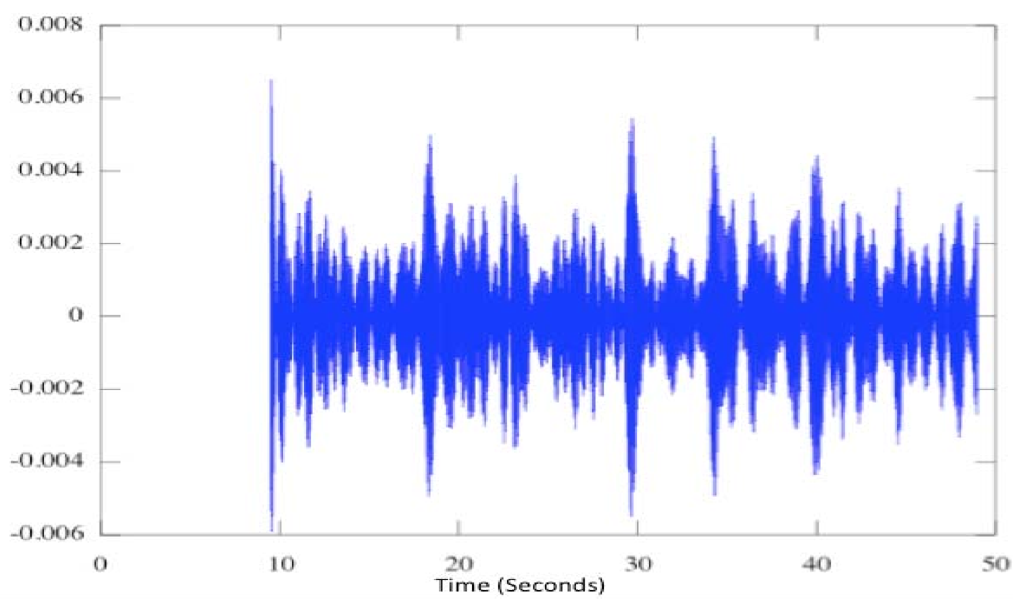

Figure 16. Second Digging Test (10 Feet)

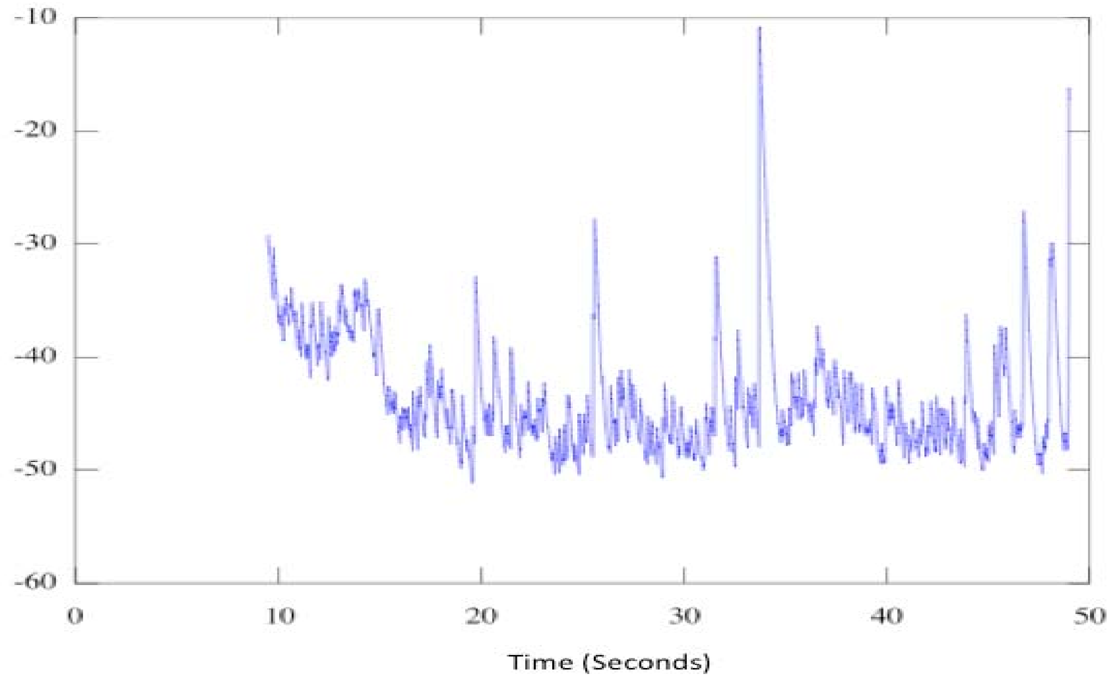

Figure 17. Second Digging Test (Audio)

The data shows that there are some significant seismic events occurring. It is correlated by the audio. In order to compare the data, we overlaid it and lined the charts up using significant events and the results can be seen in Figure 18. It is clear that several of the seismic events lined up between the two charts. There is more activity in the 5-foot chart, which is to be expected. Where these data points line up, it clearly points to the effectiveness of the sensor to detect events that were caused by the digging. The audio spikes at the expected times show the sound caused by these events.

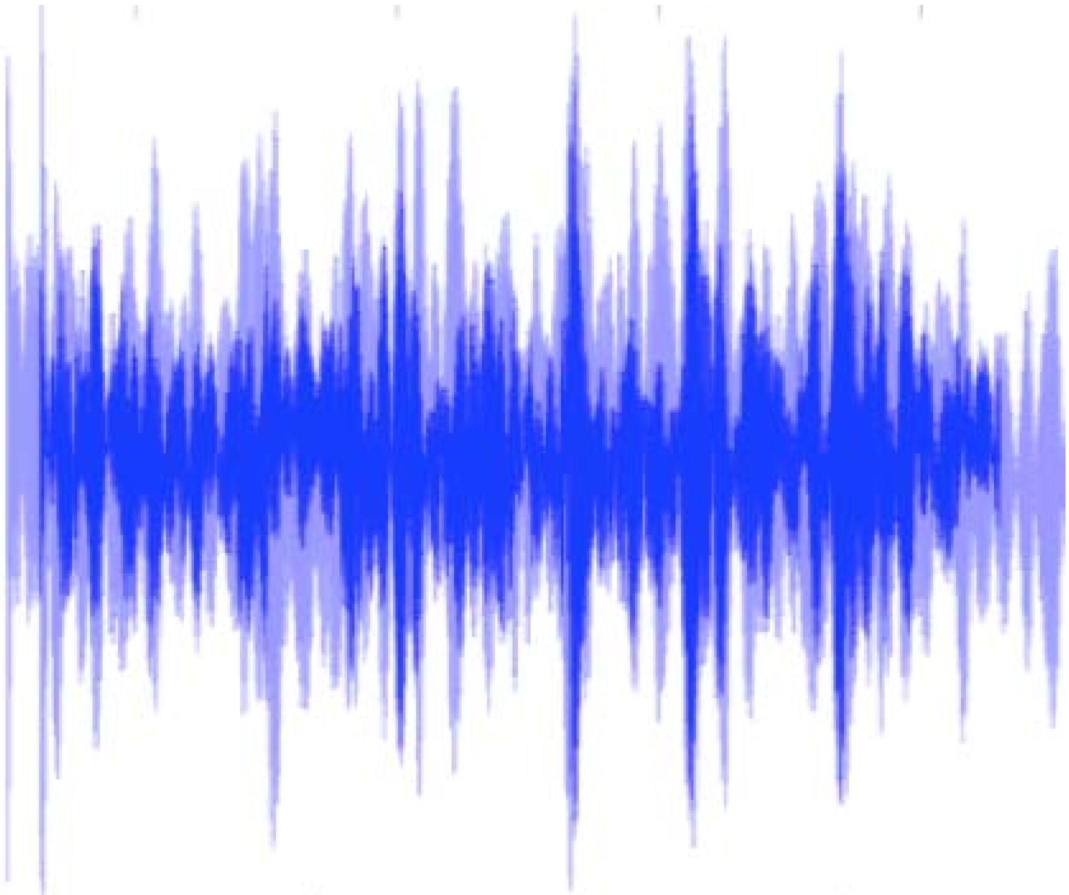

Figure 18. Digging Overlay

D. FUTURE TESTS

Future work will explore the effect of ground types. We will obtain baseline seismic data that will be preloaded into the application. The user will select the type of ground the sensors are placed in and this will change the thresholds where we are looking for anomalies. Harder packed dirt will likely carry a seismic signal longer, so the threshold can be set higher to decrease false positives. A sandy area will have very little seismic wave traffic and the audio signal will be the main source of alert detection.

E. SUMMARY AND CONCLUSIONS

The tests that we performed covered situations from indoors to outdoors and from walking to digging. The seismic signals that our IPhone captured were quite noisy. However, there were some promising results. The phone clearly recognized footsteps indoors, and an application could give alerts in that situation. Outdoor monitoring revealed a smaller radius wherein the device would recognize an event. We believe there is some noise in the device that is masking the footsteps; close passes are recognized but footsteps at a further distance disappear in the noise. Additional filtering and improved hardware could provide better results.

Chapter V is the author’s views on how these systems could be deployed in a small unit setting. It gives diagrams and scenarios on where and when to deploy sensors in order to maximize the effectiveness of the grid.

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V. APPLICATIONS

Our ground sensors have a wide range of uses to the warfighter. Consider here some scenarios based on fireteam and platoon-level offensive and defensive operations. Our current calculations have used six meters as the detection radius for any given sensor. Since we are attempting to use only Smartphone and no external gear, we have used Bluetooth that is built into the device to create an ad hoc network to transfer the alerts to the base stations. The IPhone 3GS did not provide wireless hotspots on its own, so Wi-Fi was ruled out. Another concern we have in our applications is the battery life. It would be impractical to place all four devices out for the night, since this would drain their batteries and leave the unit without their phones subsequently. Conversations with representatives from Apple Inc. reveal that they are working on this problem. They are developing portable chargers, including solar cells, to extend the length of batteries to maximize military interests in the IPhone. Other Smartphone have replaceable batteries; this would be our suggestion for purchasing Smartphone for the U.S. Military.

A. OFFENSIVE OPERATIONS

Our system could be used in many different offensive operations including ambushes and urban missions. In an ambush, the sensor could be placed in the likely avenue of approach such as a road or trail. The sensor would operate as a trigger to prepare the unit for immediate action. The sensor works well at night and for a unit sitting a long time in the ambush waiting for the ambush to develop. A

sensor placed in the avenue of approach would recognize movement giving the ambushing unit significant notice. The few seconds could mean the difference between a successful ambush with coordinated fire or an unsuccessful one where the ambush is tripped early or late. The sensor will give an accurate location of the enemy as they approach the area. Figure 19 shows an example where the enemy is expected to come from one direction. Figure 20, where the enemy's location is not known, the phone will pinpoint the direction the enemy is coming from.

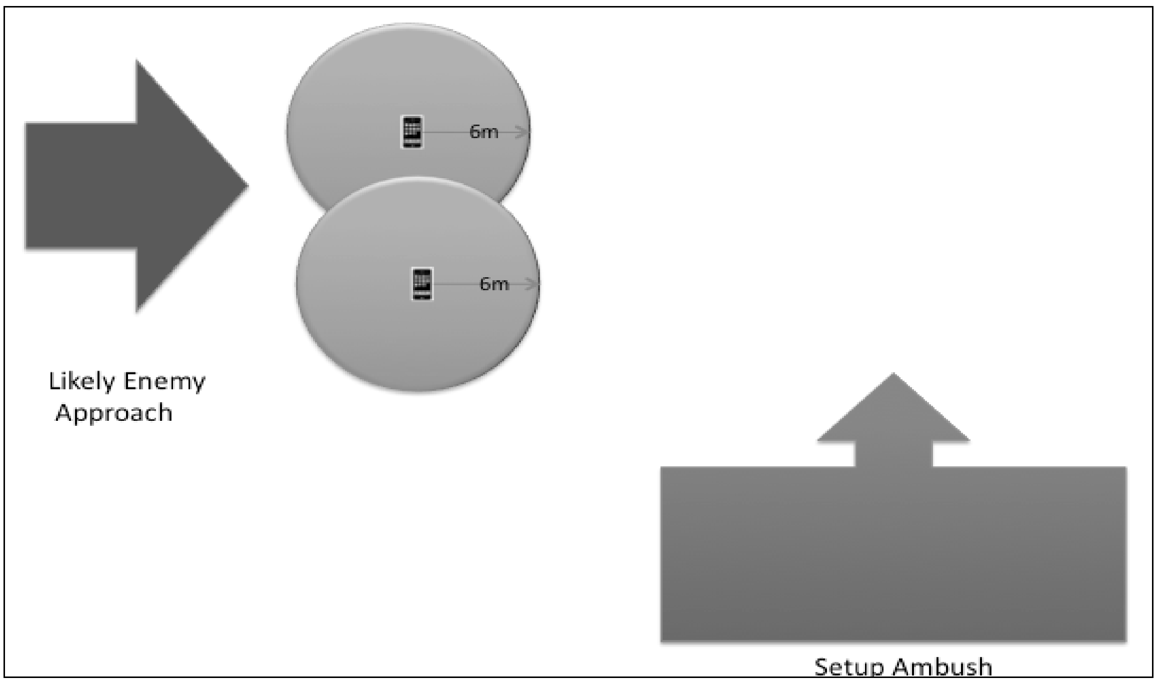

Figure 19. Ambush Example w/ Known Avenue of Approach

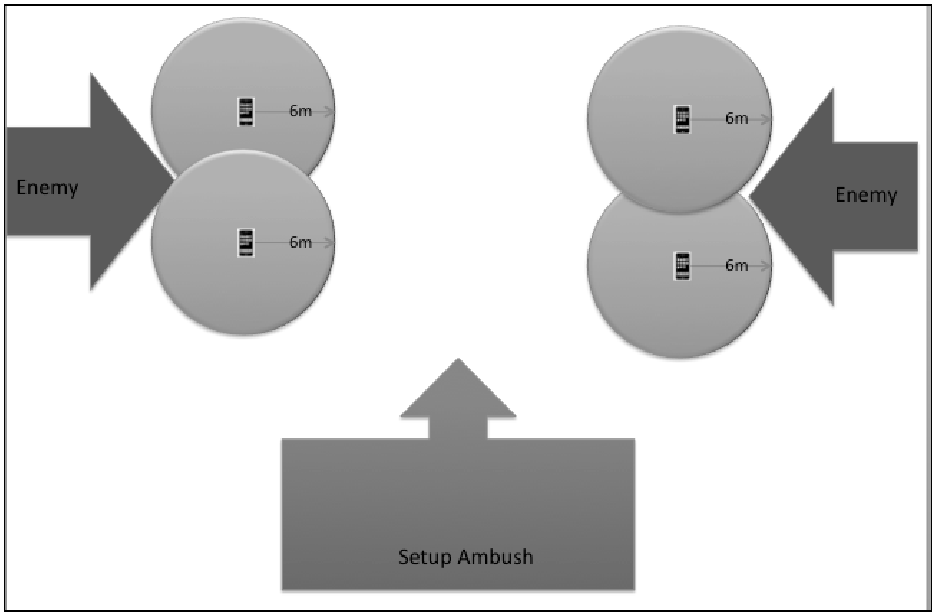

Figure 20. Ambush Example w/o Known Avenue of Approach

B. DEFENSIVE OPERATIONS

We now discuss several defensive configurations based on standard Marine Corps operating procedures. The standard deployment of teams consists of the fireteam consisting of four members. The members will keep five to twenty meters away from each other to avoid multiple casualties from a single explosion. Fireteams generally consist of a Team Leader, an Automatic Rifleman, an Assistant Automatic Rifleman, and a Rifleman. The sensors would be deployed based on needs of the mission. For instance, Figure 21 shows a deployment configuration where the team wants to deploy all of their sensors with an auditory alarm. Figure 22 shows a situation when friendly lines are known and the team wants to maximize the sensor coverage in a given direction. By deploying all four sensors for a four-person team, the team

is left without a base station; so all alarms will have to be auditory. An auditory alarm will alert the enemy to the sensor, as well as the friendly team, but it may cause confusion among the enemy while alerting the friendly team to the direction of the alarm.

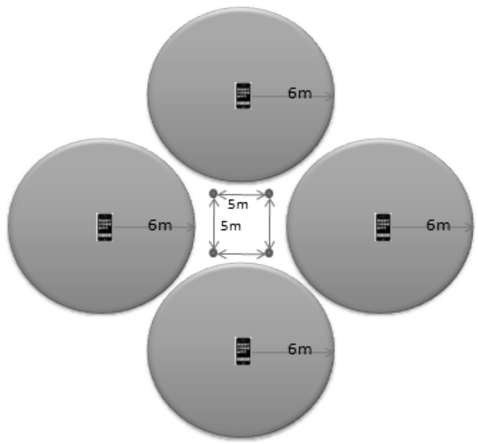

Figure 21. Defensive Example Non-Directional w/ Auditory Alarm

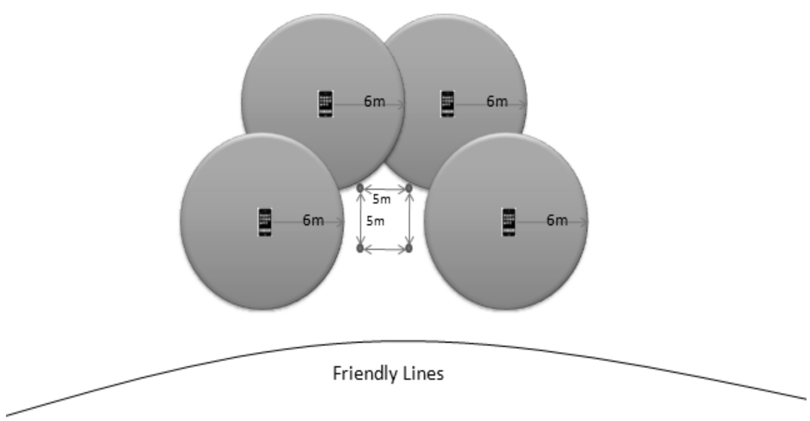

Figure 22. Defensive Example Directional w/ Auditory Alarm

If a team is deployed behind enemy lines and is trying to maintain stealth, it may be beneficial to deploy sensors with a silent alarm. The sensor array will be networked back to a base station that is monitored by the team member on watch. A tripped alarm will silently give an alert and rough direction to the watch giving him an opportunity to assess the situation and determine if an attack is imminent or can be avoided. This should give the team the few seconds of additional warning. Figures 23 and 24 show a couple examples of deployment options for such a silent array.

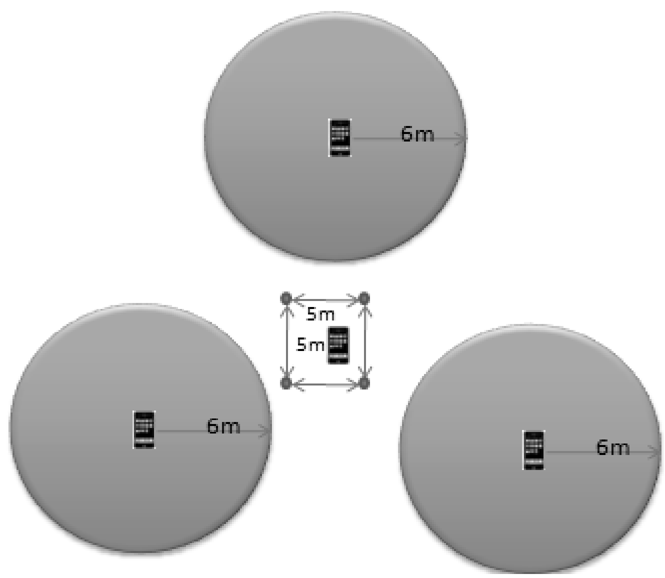

Figure 23. Defensive Example Non-Directional w/ Silent Alarm

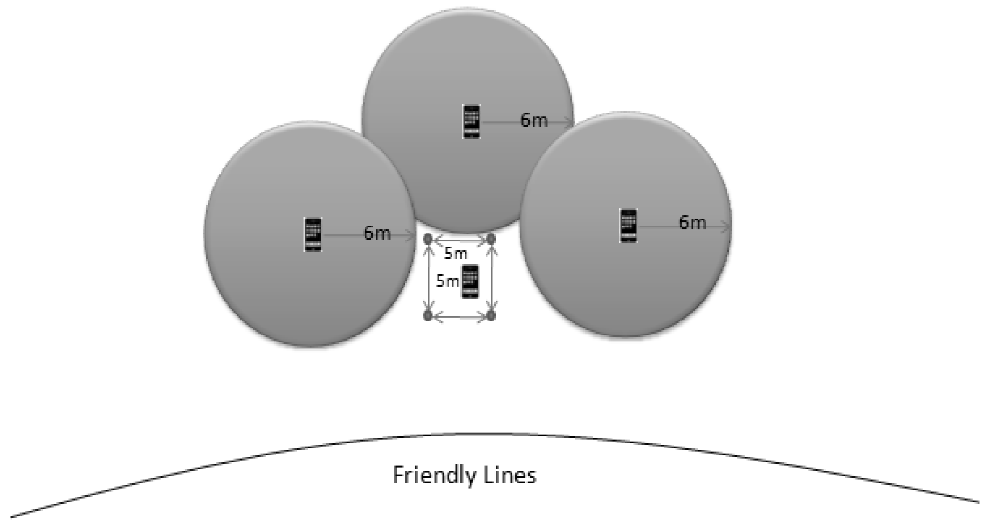

Figure 24.   Defensive Examples Directional w/Silent Alarm

The Smartphone sensors can also deployed to extend the effective range of the unit’s forward listening post. When a platoon or company sets up a defensive position, the commander is tasked with recognizing likely avenues of approach and deploying listening/observation posts The listening post is usually a two-man team placed as far as safely possible in front of friendly lines. They have a radio to call back any activity to the friendly lines. At night this post has a limited range. Figure 25 displays a situation where the sensors would be placed ahead of friendly lines to increase the effective range of a Listening Post. The nightly post is sent ahead to give the main line a pair of ears to warn the platoon of approaching enemy. Figure 26 shows how the sensors could be placed to cover areas that are hidden from a unit’s line of sight.

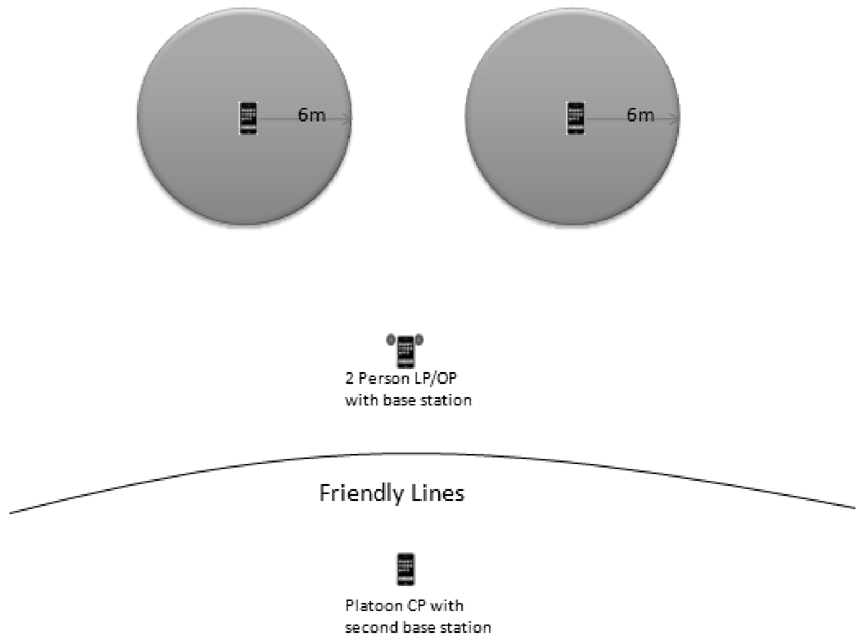

Figure 25. Listening Post Used in Platoon Defense

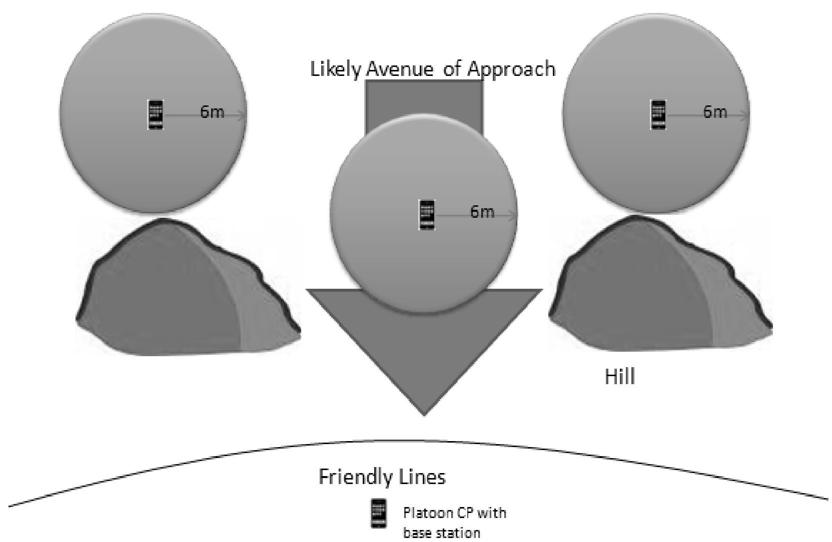

Figure 26. Platoon Defensive Examples

C. OTHER USES

The phones have also shown good detection capabilities indoors. This shows promise for the device to act as a makeshift alarm system when operating in urban terrain. A team that takes up a security position inside a building could use the phones in a number of different configurations, such as placing a phone on floors to detect movement or near entrances. The phone would be limited by the radio connection, as Bluetooth does not travel well through objects such as walls and floors.

Tripwires and other external sensors such as motion detectors would be a way that a unit could improve the accuracy of the device. A tripwire is a small wire attached to the end of the phone and a stationary object. In this way, touching the tripwire would cause a large spike in the seismic signal and would raise an instant alarm. We could again use silent or auditory alarms for the same reasons discussed above.

D. SUMMARY

This chapter discussed some of the author’s ideas on the deployment of the device in a field environment. There is a wide range of scenarios where a quick and small ground sensor could come in use. Offensive situations would allow for a trigger point for ambushes while defensive perimeters would use it to extend their ears into the dark. There was also discussion on other, non-conventional, ways to use the sensor.

The next chapter provides some concluding thoughts and areas for future work on this project.

VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

We have discussed the use of a Smartphone as an unattended ground sensor. We have discovered that the accelerometer inside the device is accurate enough to be used for military applications. The microphone is an excellent complement to the accelerometer, and a combination of both could provide a fairly accurate alert system for small unit operations. But the data we obtained in experiments contained considerable noise that is produced by the phone or accelerometer module inside the phone. This noise is the biggest obstacle in the development of a full-scale application to generate and pass on alerts to a base station. Continued filtering techniques combined with further maturing of the Smartphone accelerometer technology could provide a cleaner signal and reduce the number of false positives and provide an accurate and useful tool.

The testing we conducted provided good results in controlled environments such as a tabletop and an indoor concrete floor. Moving the device to an outdoor environment added more noise to the signal while reducing the footprint signature, which made seismic footsteps harder to detect. However, the microphone on the device provided some very promising data that showed the approach and retreat of a test subject along with individual footsteps.

The capabilities of Smartphone are improving at a rapid pace. There are already phones in the market with 1GHz processor. These phones will eliminate the need to transfer

data to another computer for processing. Also, significant amount of research is being done on improving battery technology, as well as on reducing the power consumption of the phones. These would help make applications such as ours more practical on phones.

B. FUTURE WORK

Processing of vibration and audio data from a device should be done on the device for greatest efficiency. Each sentry device should make its own assessments on raising an alert. In the IPhone, we are using Objective C to write the applications; however, the IPhone also ports the C language directly. Thus, we are attempting to use Matlab to perform calculations and we will use the abilities of Matlab to translate to C to perform the same algorithm on the phone. The kurtosis readings will take place at a set number of seconds to keep the processing down to a level where it will not cause lag in the phone.

The determination of when to raise an alert is key. We must run field tests in real environments to assess the accuracy of the device. It will require us to make determinations on acceptable levels of false positives and negatives. As we try to capture more distant alerts, we risk getting more false positive alerts caused by ground and IPhone noise.

We hope that as we improve our detection algorithms to the point were we could attach strength of alert value to an alert received. If we could determine how strong an alert is, we could guess how for away from a phone the seismic event is occurring. This would be useful as subsequent

alerts become higher or lower; then the base station would interpret this as a threat moving toward or away from the sensor.

Tests should be done to determine how multiple phones could interact with each other to give the base station a clearer picture of where an alert is originating. The base station may be able to register multiple alerts from multiple phones. These alerts would be processed based on the strength of the alert and the occurrences of alerts and the phone could be taught to determine a most likely location using triangulation.

Another concern with the current devices on the market is the length of the battery. The IPhone is especially vulnerable to this problem as there is no way to recharge it quickly. There are several solutions in the works to correct this problem. The Apple Corporation is developing mobile solar cells to charge the phone. Similar mobile charging devices could make the IPhone viable. However, several other phones such as the Motorola Droid have a replaceable battery. This would allow the operator to carry multiple batteries that could be replaced when needed.

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